

THE IMPACT OF SEA-LEVEL RISE ON SALTWATER INTRUSION FOR COASTAL
AQUIFERS IN NORTH CAROLINA

by

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Honors Thesis

Appalachian State University

Submitted to the Department of Geological and Environmental Sciences
and The Honors College
in partial fulfillment of the requirements for the degree of

Bachelor of Science

May, 2021

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Abstract

The coast of North Carolina has been identified as a sea-level rise hotspot because the coastline experiences higher rates of sea-level rise compared to the global mean level. These rising sea levels will subsequently lead to increased saltwater intrusion for coastal aquifers in this area. In this study, a head-controlled scenario is used to conduct an analysis of saltwater intrusion for coastal North Carolina under various sea-level rise scenarios. A head-controlled scenario assumes that as sea level rises, the hydraulic head will remain the same. This is likely to be the case because of groundwater extraction, evapotranspiration, and a lack of vertical mobility possible at these sites. The northern section of the coastline is subsiding while the southern portion remains stable, so the rates of sea-level rise vary from north to south. In all locations, the movement of the saltwater toe inland occurs at an exponential rate as sea level rises. Factors such as hydraulic conductivity, the thickness of the aquifer, and recharge influence the steepness of this saltwater intrusion curve. This study finds that if sea levels rise in excess of 1 m then some North Carolina barrier islands could lose the entirety of their freshwater lenses.

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1. Introduction

Saltwater intrusion is the infiltration of saltwater into the freshwater lens of surficial aquifers in coastal settings. Research of the mechanisms that influence the extent of intrusion and the dynamics of the saltwater-freshwater interface has occurred since the late 1800s (Ghyben, 1888; Herzberg, 1901). Since then, mathematical techniques have been developed to enable more complex modeling of these same aquifers (Strack, 1976; Vacher, 1988b; Ferguson and Gleeson, 2012).

A driving force behind the increase of saltwater intrusion in coastal environments is rising sea levels as a result of climate change. The effect that sea-level rise has on saltwater intrusion is particularly evident in areas with lower hydraulic gradients (Ferguson and Gleeson, 2012). Areas such as the Outer Banks of North Carolina or the coast of Louisiana are at a higher risk of saltwater intrusion driven by sea-level rise as opposed to an area with higher hydraulic gradients such as the coast of Maine (Jasechko et al., 2020). The most recent IPCC report projects the global mean sea-level to rise between 0.43 meters and 0.84 meters by 2100 (Openheimer et al., 2019). All of the projections expect the rate at which sea level is rising to increase over the next century (Oppenheimer et al., 2019). The coast of North Carolina, which is the focus for this study, is expected to have an increase in sea level of around 1.1 meters by 2100 with sea levels expected to rise more in the north than the south (Sweet et al., 2017; NOAA, 2020).

A number of studies have shown that as saltwater rises along the coast it will subsequently lead to an increase in saltwater infiltration inland (Werner and Simmons, 2009; Ferguson and Gleeson, 2012; Carretero, 2013; Custodio, 1987). As sea-levels rise along the coast, the denser saltwater will rise above where the less dense freshwater lens was prior to the rise in sea level. This is particularly likely in the case of the Outer Banks and other southeastern U.S. coastlines that have highly-permeable sandy beaches. As saline water rises above the freshwater lens, the width of the freshwater lens will decrease. This will then lead to an increase in the rate of intrusion over time as well.

The extent of saltwater intrusion is driven by both human and natural factors. Some of these human-driven factors include groundwater extraction for consumption or various land-use changes such as housing developments that can lead to erosion. As natural barriers, such as dunes, erode it can lead to easier entry of saline water onto the land surface during overwash

events. Natural variables include aquifer parameters such as the thickness of the aquifer, hydraulic gradient, and hydraulic conductivity. While the focus for this study is on the natural variables, it is important to consider the expected social and financial costs of the intrusion as well. The existence of saltwater intrusion is not unnatural or problematic when occurring at natural rates. Problems have arisen now that roughly ten percent of the world's population lives in areas that are less than 10 meters above sea level (UN, 2017). Many of these communities rely on the freshwater lens of these aquifers to supply some amount of potable water. There are also increased pollution risks for these areas because as sea levels rise past septic systems, toxic chemicals can infiltrate the freshwater lens and flow towards the ocean. This exact scenario has already led to beach closures and animal die-offs along the East Coast of the U.S. (Ebbs et al., 2020). The consequences of sea-level rise and saltwater intrusion can have far-reaching effects.

There have been a number of studies that have looked at saltwater intrusion on a broad scale to evaluate which factors play key roles in influencing the extent of the intrusion (Werner and Simmon, 2009; Ferguson and Gleeson, 2012). There have also been site-specific studies done using particular hydrogeological parameters (Carretero, 2013). The present study looks more closely at the North Carolina coast and aims to project the extent of saltwater intrusion along this stretch of coastline under various sea-level rise scenarios. This is important because the coast of North Carolina is a sea-level-rise hotspot, meaning sea-level rise is anticipated to rise more quickly than global mean levels, and the freshwater lenses of these aquifers remain vital to the water supply for some of these communities (Gehrels et al., 2020). The loss of the freshwater lens will also damage coastal ecosystems where certain species are not able to survive in increasingly saline conditions. These highly-permeable, low hydraulic-gradient beaches are perfect sites for testing a new approach to a head-controlled aquifer system when there is a lack of water-table information readily available. Projecting saltwater intrusion under various sea-level rise scenarios using hydrogeological parameters specific to North Carolina is beneficial when trying to understand the areas of the North Carolina coast that are most at risk from rising seas.

2. Sites

The mainland coast of North Carolina is around 500 km long but off of the mainland is a roughly 300 km long barrier island chain running from north to south known as the Outer Banks. The Outer Banks lie as far as 50 km off the coast of mainland North Carolina and are generally less than 1.5 km in width. Cape Hatteras and Kitty Hawk are some exceptions, where the width of the island extends to around 3 km. The eastern side of the island chain borders the Atlantic Ocean, while the western side borders various sounds, with the most notable being Pamlico Sound and Albemarle Sound. Pamlico Sound has a salinity that is approximately 60% of seawater, so the dynamics between the freshwater-saltwater interface will be different on one side of the barrier island than the other (Anderson, 2002). Other studies have researched how variations in coastal elevation between the sound and ocean side of a barrier-island aquifer can influence dynamics, but for this study, the ocean-side of the aquifer will be the primary focus (Vacher, 1988a).

The permanent number of residents on the Outer Banks is around 60,000 people, but it has a highly-fluctuating tourist population with over 1.5 million people visiting the popular tourist destination of Cape Hatteras in 2019 (Hampton, 2019). Water is primarily supplied to this population by desalinating brackish water coming from the Yorktown Aquifer at a depth of around 100 meters (Tabb, 2020). Water treatment costs can be reduced by mixing this brackish water with fresh water from the many surficial aquifers along the coast. The projected increase in sea-level combined with worsening storms and overwash events pose significant threats to future tourism and property values along the Outer Banks because of flooding and storm risks. The Outer Banks are more developed along the northern and central portions of the chain, but the narrow width and low hydraulic gradients put the long-term future of the freshwater lenses anywhere along the Outer Banks in question.

The coast of North Carolina experiences a sub-tropical climate with summer temperatures averaging around 30° C and winter temperatures averaging around 12° C. Precipitation is higher during the summer months and the Outer Banks averages around 1470 mm of precipitation a year (NOAA, 2021). Climate is an important factor in any barrier island system because recharge to the freshwater lens of the aquifer from precipitation is the primary mechanism that keeps the freshwater-saltwater equilibrium intact. The measured precipitation values do not directly translate to recharge values for the aquifer because of factors

such as evapotranspiration. Just as precipitation changes seasonally, so does evapotranspiration because as the temperature gets warmer plants extract more water from the ground. In addition to seasonal changes, there are yearly cycles such as El Niño and La Niña that can greatly influence precipitation along the coast of North Carolina (Anderson and Emanuel, 2010). These seasonal and yearly cycles cause a constantly fluctuating water table so it is important to consider that the steady-state conditions analyzed in this study look at a snapshot in time based on average values for precipitation and water-table elevations.

The focus of this study is on four locations spanning the entirety of the coast of North Carolina. The sites included are: Duck, Buxton, Emerald Isle, and Wilmington as shown in Figure 1. The only assumption that remains constant between the four locations is a constant recharge rate. Each site has an unconfined, surficial aquifer with unique hydrogeological characteristics that distinguish it from the others. The site-specific characteristics that influence the extent of saltwater intrusion in this study include: (1) the depth from the water table to the confining layer; (2) the projected sea-level rise at the aquifer's location; (3) the hydraulic conductivity of the aquifer; (4) the rate of groundwater discharge to the ocean at the site; and (5) the hydraulic gradient of the aquifer. These values come from known parameters published in other site-specific studies.

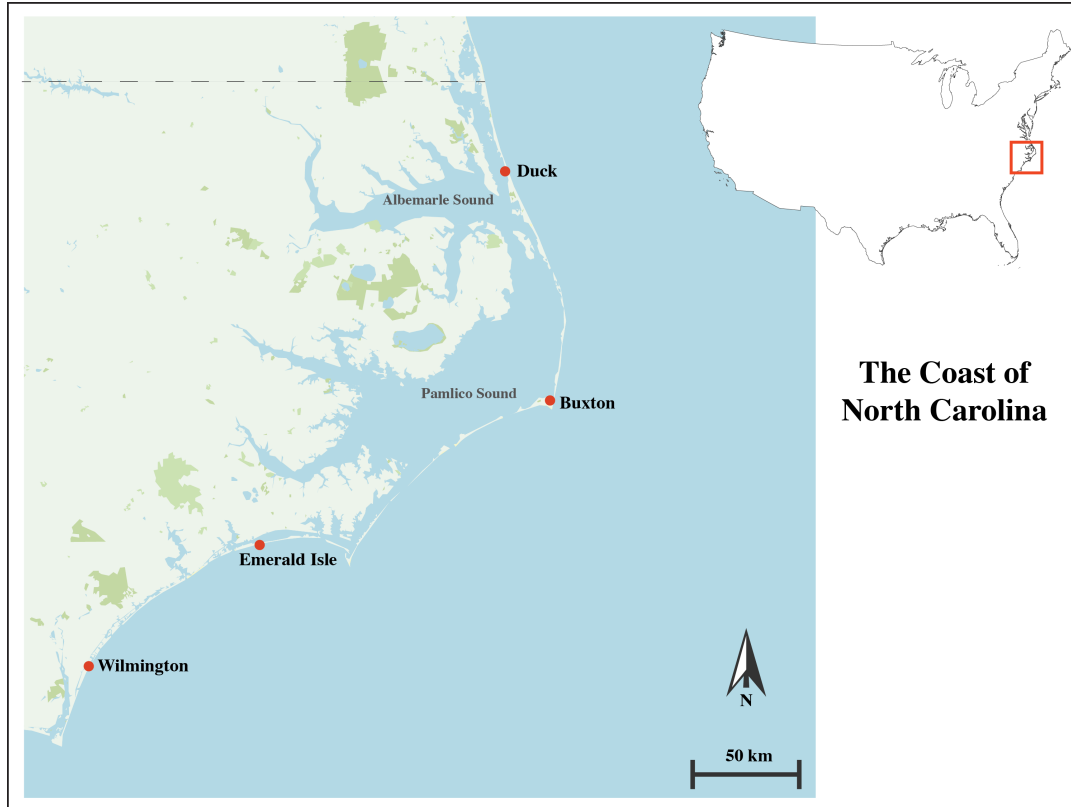


Fig. 1: The study area showing the four site locations emphasized in this study

3. Methods

3.1. Governing Equations

The analysis conducted in this study uses a modified technique for projecting the extent of salt-water intrusion, as shown in Werner and Simmons (2009), through the use of a quasi-2D steady-state analytical model. Werner and Simmons (2009) presented two approaches to studying the effects of sea-level rise on coastal aquifers: head-controlled and flux-controlled systems. A head-controlled system is a coastal aquifer system where hydraulic head remains constant even as sea level rises. This means that as sea level rises, the water table will not rise with it, so as a result hydraulic gradient will decrease in the aquifer. A flux-controlled system is a coastal aquifer where head rises at the same rate as sea-level rise to maintain a constant q value, or flux of fresh water to the ocean. The head-controlled approach was adopted rather than the flux-controlled approach for this analysis because of the type of aquifer system present along the Outer Banks: the low-elevation coastlines of North Carolina combined with highly-permeable

hydrogeological conditions means that there would be little room for vertical mobility of the water table at these sites. There are also other natural factors that could explain a lack of rising water table, such as groundwater extraction or evapotranspiration (Carretero, 2013).

The assumption of a homogenous, isotropic, unconfined aquifer experiencing a constant recharge rate under steady-state conditions was used for this study. The Ghyben-Herzberg approximation of the dynamic relationship between fluids of different densities and the Dupuit approximation for horizontal flow were also used to determine projected saltwater intrusion values (Werner and Simmons, 2009). The specific technique used in this study varied from the Werner and Simmons (2009) approach due to a limitation on information about water-table elevations for these sites. Hydraulic head values (h) were generated for any point (x) using (Fetter, 2001):

$$h^2 = \frac{R(M^2 - (M-x)^2)}{K(1+\alpha)}, \quad (1)$$

where R is the rate of recharge, M is the half-width of the site location, K is the hydraulic conductivity, and α is the density ratio between the fresh and saline water. The density ratio, α , comes from:

$$\alpha = \frac{\rho_f}{\rho_s - \rho_f}, \quad (2)$$

where ρ_s is the density of the saltwater and ρ_f is the density of the freshwater. The density ratio is generally assumed to equal 40 but has been found to increase at near shore environments under certain R and K conditions as shown in Vacher (1988b). While the value for head shown above does not factor in an impermeable base, the formula consistently yielded head values close to certain known head values from sampling done at Emerald Isle (Sisco, 2013), Nags Head Woods (Emry, 1987), and Buxton (Anderson, 2000). The use of this formula for head values creates the assumption that the midpoint of the island is where the maximum height of the water table occurs. This assumption was used for model simplification purposes because sampling done on the Buxton Woods Aquifer shows lower head values on the northern side of the aquifer where vegetation is more abundant (Anderson, 2000). A higher abundance of vegetation in certain areas is one way that an asymmetrical water table can form. The value for head was then used to calculate the discharge per unit length (q) of coastline as (Ferguson and Gleeson, 2012):

$$q = Kb \left(\frac{h_M - SLR}{M} \right), \quad (3)$$

where b is the thickness of the aquifer below sea-level, h_M is the water table elevation at the midpoint of the barrier island, and SLR is the extent of sea-level rise. Initial simulations assume a sea-level rise value of 0 m. The value for b is influenced by sea-level rise and increases through a simple addition of the sea-level rise to the baseline aquifer depth. The position of the toe of the saltwater wedge is then found as (Lu et al., 2015):

$$X_{toe} = \frac{(1 + \alpha)Kb^2}{2\alpha^2 q}, \quad (4)$$

where X_{toe} is the distance from the coastline to the tip of the saltwater wedge along the base of the aquifer. This is the value that is used to determine the extent of saltwater intrusion into the aquifer. As mentioned previously for (3), the value for b will change based on increases in sea-level. While (3) does not account for recharge to the aquifer, recharge is factored into the determination of water-table elevation for (1). Due to the narrow width of the barrier islands along the Outer Banks, it is important to factor in the lost width of the aquifer due to rising sea-levels. The lost width of one side of the aquifer is $\Delta Width$. This value exists at the point where the projected rise in sea-level meets the same point along the generated values for hydraulic head. These changes in aquifer width lead to adjusted values for X_{toe} , because as the aquifer width decreases, the change in X_{toe} for each sea-level rise scenario will have to account for the change in the width from the starting point of the aquifer. This means that the adjusted X_{toe} values will equal X_{toe} plus the $\Delta Width$ for that sea-level rise scenario. The relationship between saltwater intrusion pre and post sea-level rise can be seen in Figure 2.

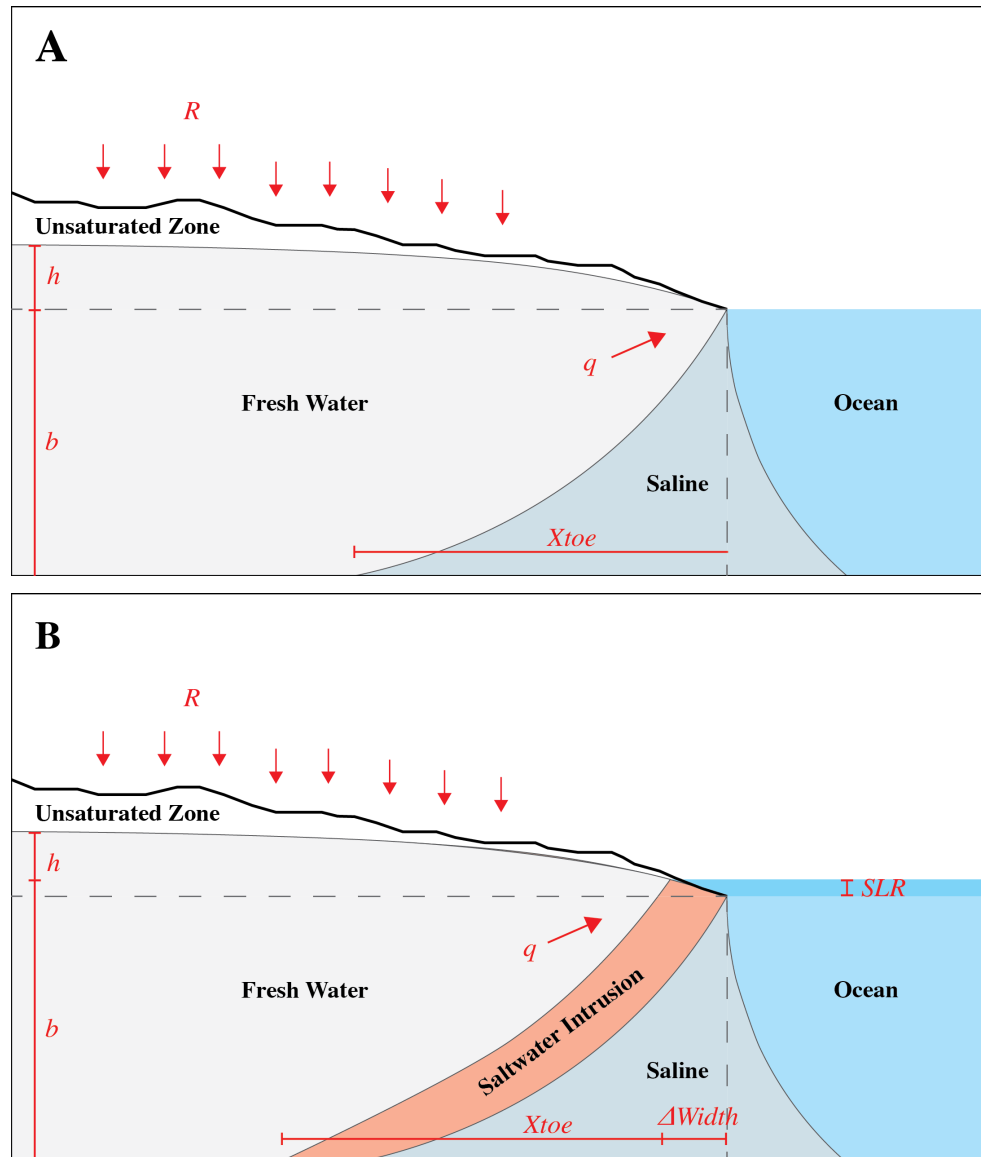


Fig 2: A conceptual diagram showing the terms used for calculating the extent of saltwater intrusion. The figure shows a before and after scenario where: (A) is the aquifer system at the baseline sea-level and (B) is the system after a rise in sea-level. The head-controlled system can be seen in this diagram because as sea-level rises, the starting line for intrusion will meet the water table where the new sea-level value occurs.

3.2. Recharge Generation

Recharge rates are generated for the sites using a combination of precipitation data and randomly generated inputs based on an analysis by Anderson and Emanuel (2010) that used Monte Carlo sampling to measure recharge fractions for various barrier island aquifer systems. Kurtzman and Scanlon (2007) found that wet El Niño and dry La Niña conditions had a significant influence on winter precipitation along the coast of North Carolina. Anderson and

Emanuel (2010) took this a step further to find the influence that El Niño and La Niña conditions had on recharge rates to barrier islands in North Carolina. These factors were used to generate recharge fractions that gave estimates of recharge to barrier island aquifers in North Carolina. One model generated in their study was calibrated specifically to Hatteras Island, which is the same location as the Buxton site used in this study, as seen in Figure 1. Due to the central location of Buxton and the similar hydrogeological parameters of the sites, the same precipitation data and recharge values were applied to each of the four sites. The reader is referred to the two previous papers for more comprehensive information related to the influence of El Niño and La Niña on precipitation and recharge.

A recharge fraction is determined by taking a calibrated value of recharge and dividing it by precipitation (Anderson and Emanuel, 2010). A value for recharge can then be approximated by multiplying a seasonal precipitation value by a seasonal recharge fraction generated from Anderson and Emanuel (2010), as shown in Table 1.

Table 1:

The recharge fraction and precipitation values used for determining recharge to the aquifer.

	Recharge Fraction ^a	Standard Deviation ^a	Precipitation ^b [mm]
Winter	0.562	0.165	343.7
Spring	0.621	0.262	304.3
Summer	0.356	0.094	405.1
Fall	0.375	0.124	421.1

^a (Anderson and Emanuel, 2010)

^b (NOAA, 2021)

Precipitation values used in this study come from monthly normal values gathered from Cape Hatteras between 1981 - 2010 (NOAA, 2021). To account for uncertainty, 250 simulations were run for each season, generating random recharge fractions in each scenario. Seasonal values were added together to find annual recharge to the aquifer which yielded a mean value of 679.5 mm/yr. The overall range of recharge values from all simulations was a minimum value of 510.4 mm/yr and a maximum of 868.4 mm/yr. These values fit well within the expected range for barrier-island aquifers in this region (Anderson and Emanuel, 2010). It is important to note that while recharge and precipitation remain constant for future projections made in this study, climate change has been shown to affect regional precipitation values and is a point of consideration for any further research (Portmann, 2009).

3.3. Aquifer Parameters

The fundamental parameters influencing the projected amounts of saltwater intrusion into the freshwater lens of an aquifer for this study are: hydraulic conductivity (K), aquifer thickness (b), width of the barrier island, and recharge to the aquifer (R). It is assumed that recharge at each of the site locations will be identical due to their relative proximity because each site has a similar climate and each site has a similar land use and land cover. The parameters for the sites are shown in Table 2.

Table 2:

Hydrogeological parameters for the site locations.

	K [m/d]	b [m]	Island Width [m]	Mean Max Head 2020 [m]
Duck ^a	10	15	1000	1.06
Buxton Woods ^b	21.2	24.5	3400	2.48
Emerald Isle ^c	4	14	1200	2.02
Wilmington ^d	15	13	1500	1.30

^a (Emry, 1987)

^b (Anderson, 2002)

^c (Sisco, 2013)

^d (Lautier, 1998)

The use of site-specific parameters works in two ways: (1) it allows for a comparison to be made between different sections of coastal North Carolina, and (2) it acts as a check on the governing equations because known head values from the studies can be compared to the modeled values for hydraulic head. The generated head values fit well within the expected values based on certain known values for hydraulic head at Emerald Isle (Sisco, 2013), Nags Head Woods (Emry, 1987), and Buxton (Anderson, 2000).

3.4. Sea-level Rise

Sea level is expected to rise at all points along the coast of North Carolina during the 21st century. With that said, the rate at which it is expected to rise varies between the northern and southern portions of the coast. The main cause of the sea-level rise variation is the rate of subsidence that happens at different rates along the North Carolina coast. The northern section of the coastline around Duck is experiencing subsidence, while the southern portion of the coastline around Wilmington is experiencing much more stable conditions (Overton et al., 2015). Table 3

shows vertical land movement at three of the study sites based on data acquired from tide gauge readings adjusted according to sea-level rise trends.

Table 3:

Rates of vertical land movement for some of the site locations. Table adapted from (Overton et al., 2015).

	Vertical Land Movement [mm/yr]	Coverage Dates
Duck	-1.49 +/- 0.39	1978 - 2013
Emerald Isle	-0.99 +/- 0.17	1953 - 2013
Wilmington	-0.39 +/- 0.19	1935 - 2013

Cape Lookout, which is slightly east of Emerald Isle, has been identified as the point at which coastal North Carolina sees an increase in the rate of subsidence (Overton et al., 2015). The 2015 North Carolina Sea Level Rise report found that tide gauge and geological data both support the conclusion that subsidence happens at a greater rate north of Cape Lookout as compared to south of Cape Lookout (Overton et al., 2015). This is important for this particular study because the site locations of Emerald Isle and Wilmington are south of this point while Buxton and Duck are located north of this point.

Most sea-level rise estimates project that sea-level will rise at an increasing rate over the next century (NOAA, 2020). The use of projected sea-level rise amounts helps to create a rough timeline of when certain model-calculated values for intrusion could occur. It is no longer a question of if sea-level is rising, but a question of when sea-level will rise to a particular point Table 4 shows the sea-level rise data used in this study.

Table 4:

Projected sea-level rise values using NOAA intermediate scenario and the NOAA Intermediate-Low or “low” scenario (NOAA, 2020).

		2040 [m]	2060 [m]	2080 [m]	2100 [m]
Duck	Intermediate	0.25	0.52	0.84	1.19
	Intermediate -Low	0.18	0.35	0.48	0.61
Buxton Woods	Intermediate	0.23	0.49	0.79	1.15
	Intermediate -Low	0.16	0.29	0.42	0.54
Emerald Isle	Intermediate	0.21	0.46	0.76	1.11
	Intermediate -Low	0.14	0.27	0.39	0.50
Wilmington	Intermediate	0.17	0.42	0.70	1.02
	Intermediate -Low	0.11	0.23	0.34	0.43

4. Results

4.1. Duck

To show the step-by-step nature for how the results were found, a detailed discussion of the site at Duck is shown first to illustrate the calculations that were performed for all of the sites. The analyses shown below were conducted for each of the 4 main sites shown in Section 4.2., and each of the 36 other sites generated for the risks maps in Section 5.2. The first step in this process requires the generation of water-table values based on recharge fractions from Anderson and Emanuel (2010). The cloud of water-table elevations resulting from the Monte Carlo simulations for recharge can be seen in Figure 3. It is not important to include more figures like Figure 3 for future years because the head values remain constant under the head-controlled scenario used in this study. The interface between saltwater and freshwater will move inland on either side of the aquifer as sea-level rises. Figure 4 shows the change in the inland migration of the saltwater toe as sea-level rises for each of the Monte Carlo simulations.

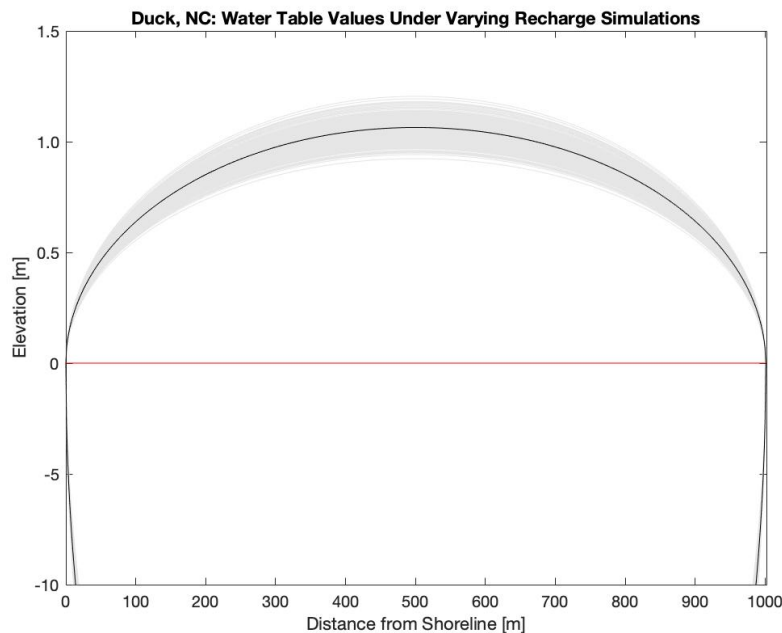


Fig 3: Cloud of projected water table values using the precipitation data from Hatteras and the recharge fractions from Anderson and Emanuel (2010) after 250 Monte Carlo realizations. The black line within the cloud is the mean predicted water-table profile based on all 250 realizations. The black lines on either side of the freshwater lens portion of the diagram are merely a diagrammatic showing of the freshwater/saltwater interface that would exist at the 2020 starting point for this study. It is important to point out that there is a 10x exaggeration of the y-axis for all values above the mean sea-level value at Duck in 2020 as shown by the red line. The red line will move upward along the figure at a rate equal to sea-level rise.

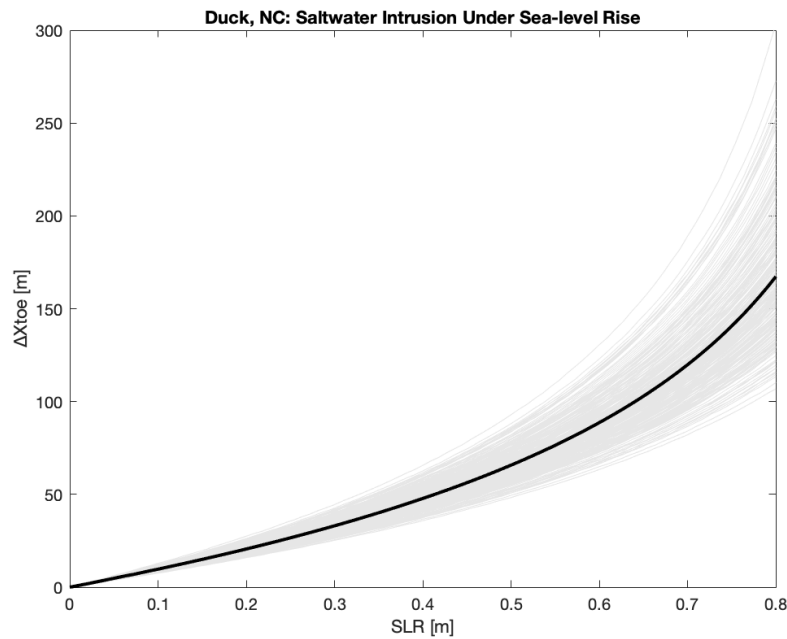


Fig 4: The change in ΔX_{toe} vs. SLR at Duck, NC for each of the 250 Monte Carlo simulations. Each ΔX_{toe} line shown above is based on a generated water-table shown in Figure 5. The darker line represents the mean value used for assessing sea-level rise scenario values shown in section 4.2.

As sea level rises, the rate of the inland migration of saltwater will increase exponentially as seen in Figure 4. This relationship is similar to results found from other studies of coastal aquifers that use head-controlled scenarios (Werner and Simmons, 2009; Carretero, 2013). This is important because not only is saltwater intrusion increasing at a non-linear rate as sea-level rises, but the most likely scenario for sea-level rise is that it will also increase at a non-linear rate over the next century. As the rate of sea-level rise increases, the rate of saltwater intrusion will also increase.

4.2. Site Analyses

Results for saltwater intrusion under the Intermediate and Intermediate-Low sea-level rise scenarios from NOAA (2020) for each site are shown below in Table 5. The values for ΔX_{toe} as sea-level rises at each of the sites can be seen in Figure 5.

Table 5:

Values of saltwater intrusion at each of the 4 sites after sea-level rise equal to the Intermediate and Intermediate-Low NOAA (2020) scenarios shown in Section 3.4. “Exceeds” means that the extent of intrusion exceeds the half-width of the island.

		2040 [m]	2060 [m]	2080 [m]	2100 [m]
Duck	Intermediate	23.5	66.5	186.0	exceeds
	Intermediate -Low	15.9	36.5	58.3	88.5
Buxton Woods	Intermediate	24.1	58.1	110.3	203.8
	Intermediate -Low	16.3	31.2	48.1	65.7
Emerald Isle	Intermediate	7.1	18.0	36.8	74.5
	Intermediate -Low	4.5	9.4	14.6	20.1
Wilmington	Intermediate	12.9	38.7	85.5	197.8
	Intermediate -Low	8.0	18.2	29.3	40.0

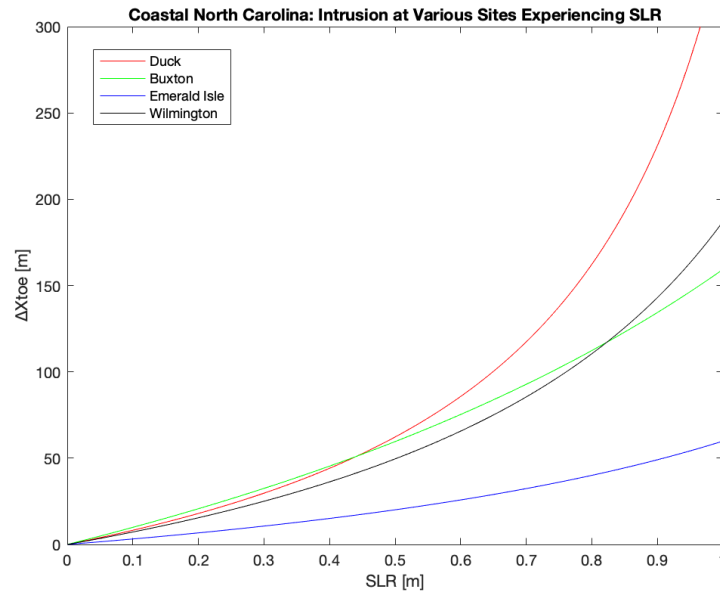


Fig 5: ΔX_{toe} vs. SLR at each of the 4 sites emphasized in this study.

The model results shown in Figure 5 indicate that the modeled rates of saltwater intrusion at each site, from high to low, are Duck, Wilmington, Buxton, and Emerald Isle. The simulations suggest

that the increased width at Buxton and the lower hydraulic conductivity at Emerald Isle are the reasons that these two sites have lower projected rates of saltwater intrusion after sea-level rise. It is important to reiterate that the rates of sea-level rise will be different at each of the four sites. The x-axis shown in Figure 5 is SLR so each site will be move along its individual saltwater intrusion curve at different rates. This is particularly evident when comparing Buxton to Wilmington. While Wilmington exceeds Buxton in intrusion under 1 m of SLR, Buxton still experiences greater projected intrusion values under both Intermediate and Intermediate-Low scenarios by 2100.

4.3. Sensitivity Analysis

It is important to consider variations in the fundamental parameters that could be present in aquifer systems along the coast of North Carolina. Data from prior literature on coastal North Carolina has K values ranging from 4 to 21.2 m/d, b values ranging from 13 to 24.5 m, and recharge rates ranging from 510.4 to 868.4 mm/yr. It is valuable to see how variations in these parameters influence the modeled trends for saltwater intrusion within this system as shown in Figures 6 through 10.

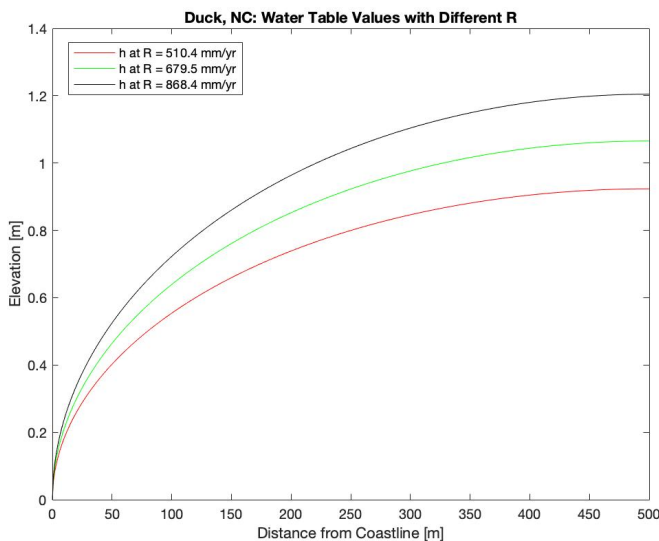


Fig 6: Modeled water table profiles with variations in R .

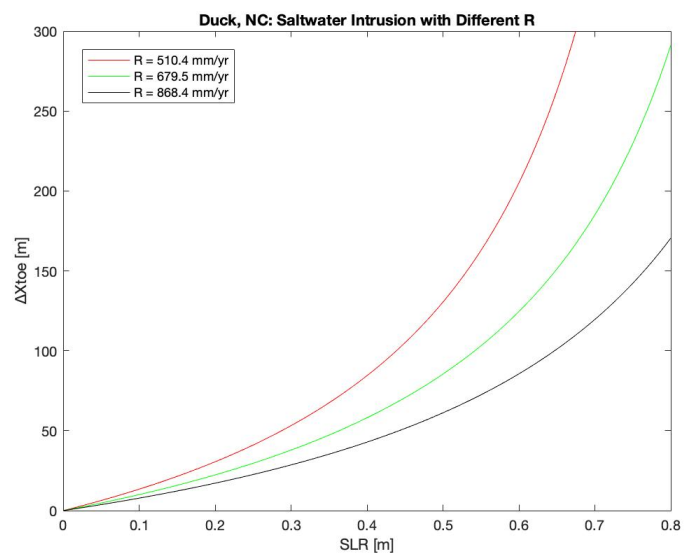


Fig 7: ΔX_{toe} vs. SLR with variations in R .

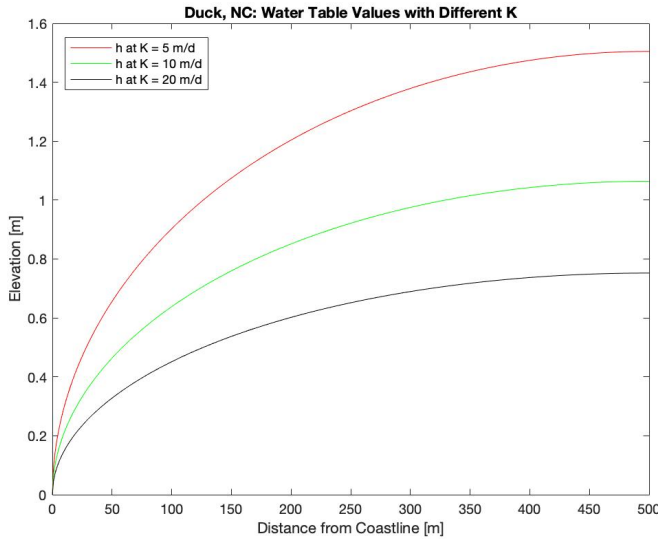


Fig 8: Modeled water table profiles with variations in K .

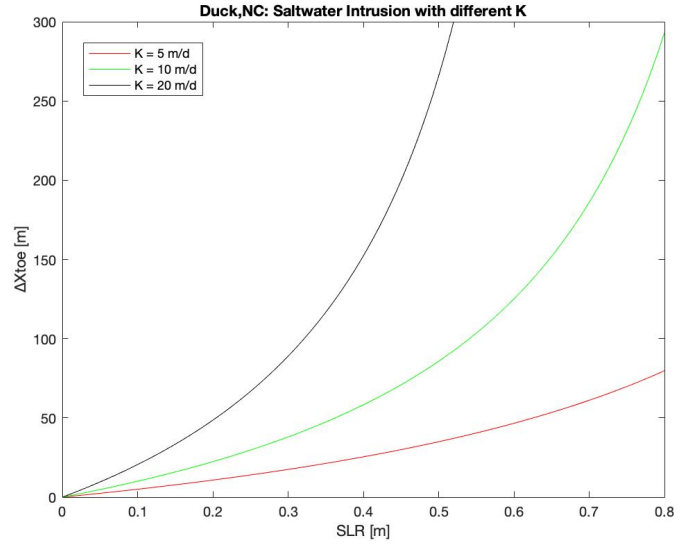


Fig 9: ΔX_{toe} vs. SLR with variations in K .

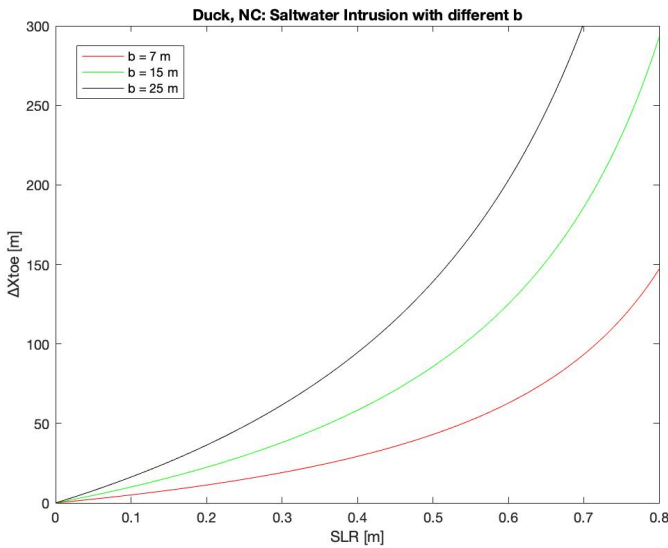


Fig 10: ΔX_{toe} vs. SLR with variations in b .

In all scenarios, when aquifer thickness (b) or hydraulic conductivity (K) increases, the intrusion curve increases in steepness. When the rate of recharge (R) decreases, the intrusion curve also increases in steepness. In addition, when R is greater, the height of the water table increases, but when K is greater the height of the water table decreases. These findings make sense based on the widely accepted understanding of these hydrogeological parameters. Out of all the varied parameters hydraulic conductivity has the largest impact on projected saltwater intrusion and modeled water-table elevations. Water table profiles with variations in b were not

shown because under the formulas shown in the Methods section the water table remains at a constant profile.

4.4. Hydraulic Gradient

As sea-level rises, the hydraulic gradient will decrease for each of these aquifer systems. As hydraulic gradient decreases, flow per unit length of coastline (q) will also decrease. This is important because the outward flow of water towards the ocean plays a major role in keeping the saltwater/freshwater interface in place and also influences nearshore water quality. If sea level is rising and water flowing towards the sea decreases, then the chemistry of the nearshore environment will change. Coastal ecosystems will be impacted by this relatively quick increase in salinity. Ferguson and Gleeson (2012) used a hydraulic gradient of 0.001 as a cutoff point for determining when saltwater inundation will become particularly severe. Saltwater inundation is the landward migration of the coastline while saltwater intrusion is the landward migration of the saltwater toe (Ferguson and Gleeson, 2012). This is factored into calculations done in this study by decreasing aquifer width as sea-level rises. Table 6 shows the estimated year and the amount of sea-level rise required for each site to pass the 0.001 cutoff.

Table 6:

Values for site specific sea-level rise and the estimated year at which the gradient at each site is expected to go below the 0.001 cutoff. The Intermediate scenario from NOAA (2020) was used to find the estimated year as it is the more likely of the two sea-level rise scenarios used in this study. Emerald Isle is blank in the above table because the site does not cross the 0.001 cutoff prior to 2100.

	SLR [m]	Estimated Year
Duck	0.57	2065
Buxton Woods	0.79	2081
Emerald Isle	-	-
Wilmington	0.56	2070

4.5. Aquifer Volume Loss

As sea-level rises, the freshwater content of the aquifer will decrease as saltwater infiltrates. Fresh water in these surficial aquifers is an important source of clean water for coastal communities, so it is important to project the loss of this resource. A simple integration was run at each site to find the aquifer volume remaining per unit width at any given moment as sea level rises and saltwater intrusion increases. The volume in this instance is of a 1-meter wide slice of the aquifer and not of the full volume of each study site. The percentage of fresh water remaining in each coastal aquifer compared to the 2020 amount under the sea-level rise scenarios is shown

in Table 7. The percentage of aquifer volume remaining per unit width at each site is shown in Figure 11.

Table 7:

Values for the estimated percent of aquifer area remaining under Intermediate and Intermediate-Low sea-level rise scenarios from NOAA (2020). Exceeds in this instance does not necessarily mean a complete loss of freshwater but a small amount where fresh water no longer extends to the base of the aquifer.

		2040 [%]	2060 [%]	2080 [%]	2100 [%]
Duck	Intermediate	94.4	79.4	39.5	exceeds
	Intermediate-Low	96.7	90.1	82.4	71.4
Buxton Woods	Intermediate	98.9	96.5	92.0	83.8
	Intermediate-Low	99.4	98.5	97.3	95.9
Emerald Isle	Intermediate	99.0	96.1	90.3	79.2
	Intermediate-Low	99.5	98.5	97.2	95.5
Wilmington	Intermediate	98.3	91.9	78.1	47.8
	Intermediate-Low	99.1	97.2	94.4	91.5

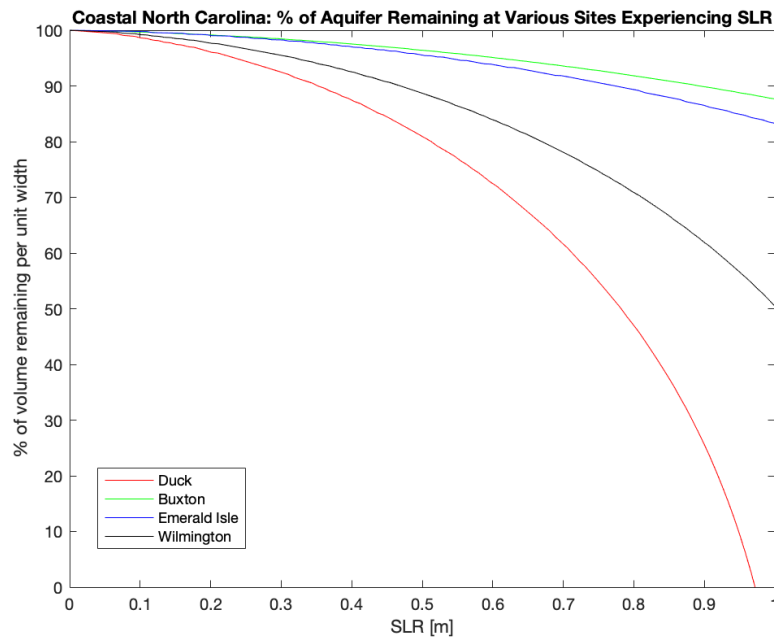


Fig 11: Percentage of aquifer volume remaining vs. SLR at the 4 sites emphasized in this study.

The results for the analysis of percent of volume remaining per unit width, much like the analysis of ΔX_{toe} vs. SLR, show an exponential change as sea-level rises. The lower hydraulic conductivity at Emerald Isle and the increased aquifer width at Buxton insulate these two sites from the worst effects of rising sea levels and saltwater intrusion. These results emphasize the

concerns for Duck, because not only is sea level rising the quickest in that location, but it also is projected to lose its aquifer volume at the highest rate compared to the other sites in this study. It is also important to consider that while this study, like most coastal aquifer studies, uses a sharp interface between freshwater and saltwater, it is more likely that a wider mixing zone will form between the two. This means that some of the area considered to be freshwater in this study, is likely more saline than normal freshwater.

5. Discussion

As sea level rises, the fresh water in coastal aquifers is under increasing threat. The mechanism used in this study to determine the extent of intrusion is based on the migration of the saltwater toe into the freshwater lens. This is the distance from the original coastline in 2020 to where the saltwater/freshwater interface connects with the impermeable base of the aquifer. While this method is commonly used for projecting intrusion, it relies on a number of assumptions that may not fully account for all of the potential future risks of saltwater intrusion.

One of these assumptions is of a sharp interface between saltwater and freshwater. While this is a common assumption made in coastal aquifer studies, a more realistic scenario is one where there is a transition zone that moves from saline to fresh water in a non-instantaneous manner. The use of a sharp interface discounts the influence of tidal processes, waves, and severe storms on the salinity of the aquifer in the nearshore environment. This influence can be negligible in situations where the aquifer has a large width, but this is not necessarily the case for narrow barrier-island aquifer systems. With that said, the use of a sharp interface model can still yield important information regarding the potential future trends for water loss in these coastal aquifers.

Another assumption made in this study that will be explored later in this section is that the entirety of the aquifer is experiencing identical influences on the water-table. These influences could be human influences from pumping or land-use change affecting recharge, or they could be natural influences such as equivalent amounts of precipitation and evapotranspiration across the entirety of the landmass or even salinities between the adjacent water bodies. Figure 12 shows that these factors not only influence the height of the water table, but also where the highest elevation of the water table occurs. In most cases, information outside the scope of this study would be required to make any kind of accurate adjustment to the model.

It is important to note that the influence of sea-level rise on saltwater entering the freshwater lens is not limited to saltwater intrusion. Climate change will not only cause rising sea levels, but will also cause more frequent and more intense natural disasters such as hurricanes and tropical storms (Collins et al., 2019). Hurricanes can cause overwash events which will lead to saline water infiltrating the freshwater lens from the top rather than directly from the coastline. Anderson (2002) found that chloride concentrations in the Buxton Woods Aquifer at Cape Hatteras can remain above the maximum contaminant levels (MCL) allowed in drinking water for over a month after severe overwash events. In instances where overwash events occur in quick succession, chloride concentrations can remain above the MCLs for over 100 days (Anderson, 2002) or never reach the idealized freshwater lens (Anderson and Lauer, 2008). As sea-level rise causes hydraulic gradients to decrease under the head-controlled system, it makes sense to assume that overwash events will worsen for these aquifer systems. While saltwater intrusion will steadily increase over the next century, it is important to consider the worsening and more frequent overwash events that will also increase salinity within these coastal aquifers.

5.1. Variations Between the Sound and Ocean

Figure 1 shows that the barrier-island chain of the Outer Banks is often adjacent to different bodies of water on either side. In the northern and central section of the coast, the Outer Banks have Albemarle or Pamlico Sound on the western side and the Atlantic Ocean on the eastern side. The differences in these bodies of water can have an influence on water-table profiles, as well as other natural factors not directly considered in this study such as varying tidal conditions, salinities, wave influence, and the ease of overwash.

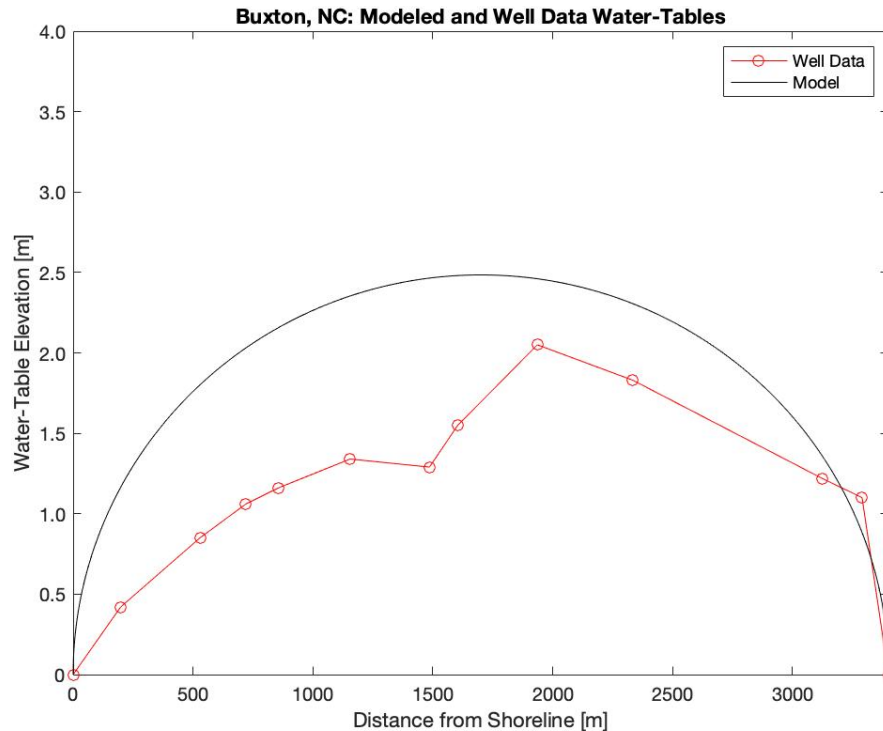


Fig 12: Two different water-tables for Buxton, NC. The black line indicates the modeled water-table generated in this study and the red indicates mean water-table values from Anderson et al. (2000).

The biggest visual distinction between the two is the difference in symmetry. The modeled water table assumes that each side of the barrier-island is exactly the same and is completely uniform. The actual water-table data are affected by more real-world factors where the assumption of uniformity does not practically apply. While the modeled water table generated from this study has a higher elevation than the mean well data, it is well within a reasonable range based on mean water-table values shown in Anderson et al. (2000). At Buxton there is more vegetation on the north side of the island as compared to the southern section, so evapotranspiration rates are higher. There are also multiple drainage ditches along the northern section of the island that drain water from the northern section of the aquifer (Anderson et al., 2000). These factors have an effect on the aquifer and this is shown in Figure 12 because the maximum water-table value is not directly in the center, but it is shifted to the south by approximately 500 meters.

Table 8:

Model outputs for Buxton, North Carolina, when the maximum water table elevation is moved 500 m towards the southern section. M is equal to the half-width of the island.

	M [m]	Hydraulic Gradient	q [m ² /d]	X _{toe} [m] *
Northern Section	2200	0.00113	0.59	165.6
Southern Section	1200	0.00207	1.08	151.5
Uniform Aquifer	1700	0.00146	0.76	214.6

* X_{toe} for the Northern Section uses a different density ratio (2) because Pamlico Sound is only around 60% the salinity of the Atlantic Ocean.

The values for “Uniform Aquifer” in Table 9 are the starting values in 2020 under the baseline conditions used throughout this study. The Northern and Southern sections are adjusted baseline conditions for 2020 when certain real-world factors are considered. The mid-point of the aquifer was adjusted 500 m to the South to line up more closely to the well data shown in Figure 12.

Another important characteristic that was considered was the different density ratios between the Northern and Southern sections of the aquifer. Pamlico Sound is around 60% the salinity of seawater so the density ratio for the northern part of the island is around 66.7 while the southern section used the established seawater/freshwater density ratio of 40.

The Southern section of the island is expected to experience less saltwater intrusion when the maximum water-table elevation is shifted 500 m south. This makes sense because a movement of the maximum water-table elevation will cause an increase in hydraulic gradient for that side of the island. Increasing hydraulic gradient leads to an increase in q, and this increase in q will lead to a decrease in intrusion. The inverse of this is true for the Northern section of the island but with one important caveat: the density ratio is different when salinity is different. Under normal density ratio conditions, the northern section of the island would have had an X_{toe} value of 277.7 m. This, however, is not the case, because as mentioned above, Pamlico Sound is only 60% the salinity of seawater. An increase in density ratio, caused by a decrease in density, will lead to a decrease in projected intrusion values. This also makes sense because as the density difference decreases, there will be less of a gravitational force pushing against the fresh water by the saline water. One factor not considered in this study is that there could be a variation in the sea levels on either side of the barrier island. If sea level is higher on one side of the island when compared to the other side, then it will lead to an asymmetrical water table that

shifts toward the side with lower water levels (Vacher, 1988a). There is room to explore the potential influence of unequal sea-levels on saltwater intrusion in further research.

5.2. North Carolina Risk Maps

The final step taken for this study was to do a general overview for the entirety of the North Carolina coast. This was done by taking the aquifer parameter values in Table 2 and interpolating K , b , and SLR values between each of the emphasized site locations. A couple site locations were also generated north of Duck, and south of Wilmington by extrapolating the same parameter trends in those directions. It should be noted that the SLR values used for these risk maps is the Intermediate scenario values from NOAA (2020). The final values required for these new extrapolated sites are aquifer width values. With the assumption that hydraulic head equals zero where the ocean meets the coastline, aquifer width values were equal to the width of the land. These width values were generated from a combination of measurements and estimations using Google Maps. In total, 36 new sites were derived from this process of interpolating and extrapolating for a total of 40 sites when including the original 4 locations.

With aquifer parameters generated for the 36 new sites, the same methods shown in Section 3 were conducted on each of the sites. This yielded saltwater intrusion values for all 36 new sites under projected sea-level rise values for 2040, 2060, and 2080. The determination of risk in this context comes from the percentage of aquifer width that is experiencing some amount of intrusion. These values were generated for each of the 40 sites in 2020, 2040, 2060, and 2080 by dividing the amount of total intrusion by the half-width of the site. In the case where the percentage exceeds 100, it is assumed that the freshwater lens no longer meets the base of the aquifer. The reason for this assumption is that based on the assumption of symmetry on either side of the island used in this study, meaning that the X_{toe} values would meet in the middle of the island and a connection to the base of the aquifer would be lost. The results from this analysis can be seen in Figures 13.

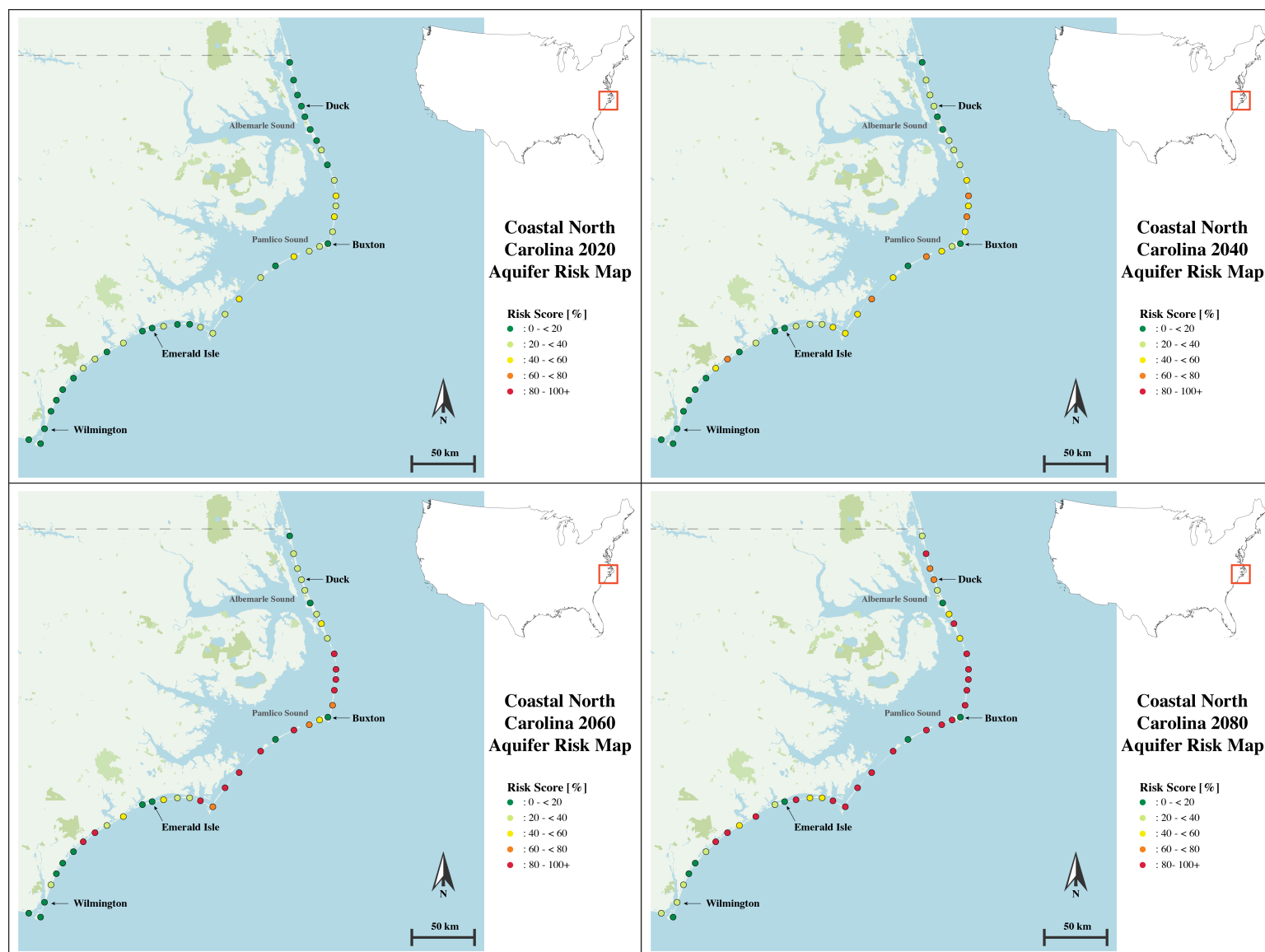


Fig. 13: Risk scores for each of the 36 generated sites, and the 4 known sites in 2020, 2040, 2060, and 2080.

While the generated parameters for the extrapolated sites rely on some significant assumptions, the trends that can be seen in Figure 13 are generally in line with what is to be expected based on the information shown earlier in this study. The southern section of the coast is generally at lower risk than the middle to northern portions of the coast. In most cases, the factor that led to the most significant increase in risk was the width of the section of coastline. A good example of this can be seen with the adjacent circles located directly below the Pamlico Sound label. These sites represent the eastern and western portions of Ocracoke Island and while it is difficult to see from the map, the width of these two sections are quite different. The eastern

section is around 700 meters in width while the western section is around 2500 meters in width. This means that even though the sites have relatively similar hydrogeological parameters, the width of the eastern section leads to a more significant amount of intrusion relative to the width of that section of the island. This method could easily be used for other barrier-island dominated coastlines around the world and creates a good baseline for understanding which portions are at the most risk.

6. Conclusion

Due to climate change, sea level is expected to rise in most coastal areas around the world. The IPCC projects an increase in global mean sea level between 0.43 meters and 0.84 meters by 2100 (Openheimer et al., 2019). This, however, is not the case everywhere because certain areas, such as the coast of North Carolina, have been identified as a sea-level-rise hotspots that are influenced by local conditions (Gehrels et al., 2020). In the case of coastal North Carolina, sea level is expected to rise by approximately 1.1 meters by 2100 (NOAA, 2020). Understanding and projecting sea-level rise is important because it will have an impact on every single coastal aquifer in North Carolina.

Rising sea levels will lead to an increase in saltwater intrusion, which in this study is measured as the amount of landward migration by the saltwater toe. As sea-level rise occurs, the hydraulic gradient within coastal aquifers will decrease, leading to a decrease in outward flow of water. This decrease in flow per unit width (q) is a primary reason for the movement of the saltwater/freshwater interface because as the force pushing against the saline water decreases, the saline water will move inland. An increase in saltwater intrusion will have an effect on the freshwater resources that remain in these aquifers, which is relied on by many coastal communities.

The model used in this study works under the assumption of head-controlled conditions. This means that as sea-level rises, the hydraulic head will remain constant. This study found that under a head-controlled scenario, rising sea levels will lead to an exponential increase in saltwater intrusion for these coastal aquifers. These findings are consistent with past studies that use a head-controlled scenario (Werner and Simmons, 2009; Carretero, 2013). This exponential increase in intrusion is exacerbated by the fact that the rate of sea-level rise is anticipated to increase over the next century as well. Under intermediate sea-level rise projections for 2100, the

increase in saltwater intrusion from 2020 values is expected to range between 74.5 m and 203.8 m at the 4 primary sites reviewed in this study. In the case of Duck, saltwater intrusion is expected to exceed the threshold at which the freshwater lens still connects with the base of the aquifer. This wide range of projections is due to key hydrogeological parameters that can have a major influence on an aquifer's ability to retain its freshwater lens.

Much like the projected intrusion values, the percentage of aquifer volume remaining per unit width also varies widely from site to site. The percentage of aquifer volume remaining per unit width is estimated to range between 83.8% and 47.8% by the year 2100 under Intermediate sea-level rise projections. In the case of Duck, the loss of the connection between the freshwater lens and the base of the aquifer at Duck can be interpreted as a nearly complete loss of aquifer volume at that particular site. As mentioned previously, it is important to consider the extreme likelihood of a mixing zone rather than a sharp interface so the percentage of aquifer volume remaining per unit width is likely a conservative estimate. While some of the communities in these coastal areas no longer exclusively rely on the freshwater lens for drinking water, the loss of this freshwater source will have a serious influence on coastal ecosystems.

The findings in this study provide a good framework for further research on the influence of sea-level rise on saltwater intrusion. Each coastal region has intricacies that are not easily integrated into one consistent model, but this model presents a method of quantifying saltwater intrusion risk in the cases of varying salinity, and in the case where there is a lack of well data for a particular coastal site. The results of this study show that the risk of saltwater intrusion cannot be assumed exclusively based on sea-level rise, but other key hydrogeological parameters can have a large influence on the migration of saltwater inland over time.

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